Agricultural Water Management 213 (2019) 843–857

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

# Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina

Joop Kroes[a,*], Jos van Dam[a], Iwan Supit[b], Diego de Abelleyra[c], Santiago Verón[c], Allard de Wit[d], Hendrik Boogaard[d], Marcos Angelini[e], Francisco Damiano[c], Piet Groenendijk[f], Jan Wesseling[a], Ab Veldhuizen[g]

[a] Wageningen University and Research, Chair Soil Physics and Land Management, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[b] Wageningen University and Research, Chair Water Systems and Global Change, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[c] Instituto Nacional de Tecnología Agropecuaria (INTA), Instituto de Clima y Agua, Castelar. N. Repetto y De Los Reseros s/nº (B1686WAA), Hurlingham, Buenos Aires, Argentina
[d] Wageningen University and Research, Wageningen Environmental Research, Unit Earth Observation and Environmental Informatics, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[e] Instituto Nacional de Tecnología Agropecuaria (INTA), Instituto de Suelos, Castelar. N. Repetto y De Los Reseros s/nº (B1686WAA), Hurlingham, Buenos Aires, Argentina
[f] Wageningen University and Research, Wageningen Environmental Research, Unit Sustainable Soil Use, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[g] Wageningen University and Research, Wageningen Environmental Research, Unit Soil, Water and Land Dynamics, P.O. Box 47, 6700 AA, Wageningen, the Netherlands

ARTICLE INFO

*Keywords:*
Groundwater recharge
Capillary rise
Land use
Soybean
Pampas
Argentina
SWAP
WOFOST

ABSTRACT

This paper studies the changes of groundwater, climate and land use in the Pampas of Argentina. These changes offer opportunities and threats. Lowering groundwater without irrigation causes drought and successive crop and yield damage. Rising groundwater may alleviate drought as capillary rise supports root water uptake and crop growth, thus narrowing the difference between potential and actual yields. However, rising groundwater may also limit soil water storage, cause flooding in metropolitan areas and have a negative impact on crop yields. Changing land use from continuous soy bean into crop rotations or natural vegetation may decrease groundwater recharge and thus decrease groundwater levels. In case of crop rotation however, leaching of nutrients like nitrate may increase.

We quantified these impacts using integrated dynamic crop growth and soil hydrology modelling. The models were tested at field scale using a local dataset from Argentina. We applied distributed modelling at regional scale to evaluate the impacts on groundwater recharge and crop yields using long term weather data.

The experiments showed that threats arise from continuous monotone land use. Opportunities are created when a proper balance is found between supply and demand of soil water using a larger differentiation of land use. Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels.

Modelling tools clearly support the evaluation of the impact of land use and climate change on groundwater levels and crop yields.

## 1. Introduction

Groundwater recharge results from the dynamic interaction between climate, land use and soil hydrology as it occurs in the critical zone, a thin portion of the biosphere connecting the lithosphere, atmosphere and hydrosphere (Amundson et al., 2007). Within this critical zone a dynamic interaction occurs between soil, atmosphere and water. The variation of this interaction in space and time can be very large and

* Corresponding author.
*E-mail addresses:* joop.kroes@wur.nl (J. Kroes), jos.vandam@wur.nl (J. van Dam), iwan.supit@wur.nl (I. Supit), deabelleyra.diego@inta.gob.ar (D. de Abelleyra), veron@agro.uba.ar (S. Verón), allard.dewit@wur.nl (A. de Wit), hendrik.boogaard@wur.nl (H. Boogaard), angelini.marcos@inta.gob.ar (M. Angelini), Damiano.Francisco@inta.gob.ar (F. Damiano), piet.groenendijk@wur.nl (P. Groenendijk), jan.wesseling@wur.nl (J. Wesseling), ab.veldhuizen@wur.nl (A. Veldhuizen).

https://doi.org/10.1016/j.agwat.2018.12.008
Received 27 May 2018; Received in revised form 18 November 2018; Accepted 3 December 2018
Available online 11 December 2018

is influenced by human and natural activities. Especially in flat, poorly drained sub-humid plains, such as the Argentine Pampas, the Brazilian Pantanal, the Canadian plains of Manitoba and Saskatchewan and the Great Plains of Hungary and Western Siberia, groundwater rise may cause large episodic floods (Aragón et al., 2010). This interaction has a large uncertainty which one wishes to minimize, especially to predict the effects of climate change and land use on groundwater recharge conditions (Smerdon, 2017). To improve the accuracy of model outputs, proper evapotranspiration data as upper boundary condition and the use of remote sensing information is recommended (Doble and Crosbie, 2017).

Mercau et al. (2016) analysed the impact of climate, topography and crop choice on the dynamics of groundwater table levels for five years on a typical farm in the Western Pampas of Argentina. They concluded that maintaining crops that increase evapotranspiration and reduce groundwater recharge for long time periods this should magnify the effects of land use on the dynamics of groundwater tables.

Vazquez-Amabile et al. (2013) applied the field-scale hydrological model DrainMod (Skaggs et al., 2012) at 12 farms fields within a radius of 100 km in the western Buenos Aires Province. They observed groundwater table depths generally within 3 m below the soil surface and concluded that leaching of nitrate should be considered since 52% of the observations exceeded the threshold of 10 mg/l $NO_3$-N. A significant proportion of the leached nitrate originates from mineralization of organic matter (Vázquez-Amabile et al., 2017).

Viglizzo et al. (2009) found correlations between groundwater level and flooding in 12.4 million hectare of the Pampas in Argentina with highly significant relations in the highlands. They also stated that land use could be steered to minimize the impact of floods.

A better understanding of the underlying processes by which crops influence groundwater is essential for the evaluation of different measures to influence groundwater recharge. García et al. (2017) applied the regional MIKE-SHE model to a sub-basin in Argentina and concluded that land use has strong effects on groundwater levels. They remarked that land use decisions to control groundwater and minimize negative effects on agricultural production should have a broad consensus regarding social and physical aspects. The water contribution from groundwater located approximately 1.5 to 2 m deep can represent up to 30% of the water requirements of soybeans in the flooding sandy Pampas, thus stabilizing the inter-annual variability of soybean yields (Videla Mensegue et al., 2015). Sainato et al. (2003) reported increasing salinity values in groundwater for the region around Pergamino where the aquifer shows an increase in water salinity to the West.

Aragón et al. (2010) used satellite data and groundwater monitoring wells to analyse the changes of groundwater depths and surface water amounts of the Western Pampas of Argentina during the flooding cycle of 1996–2006. They showed that mean regional groundwater levels rose by 2.5 m in 5 years, which decreased the average vadose zone from 3.7 m to 1.2 m. In the same period, the regional surface water coverage (ponds, rivers, lakes) increased from 3% to 28% primarily by the development of new water bodies. This had a huge impact on hydrological connectivity throughout the landscape transport and flooding risks. Kuppel et al. (2015) extended the hydrologic analysis of the Pampas to the period 2000–2013 and included the eastern lower part of the Pampas. They investigated three responses to periods with increased rainfall: (i) increased water storage leading to rising groundwater tables and floods, (ii) higher evapotranspiration losses favoured by higher soil moisture contents and capillary rise and, at very high levels of water storage, (iii) enhanced surface water outflows favoured by the surface water connectivity. They concluded that the first two responses are dominant: rising groundwater tables and higher evapotranspiration losses.

A better understanding of the complex interactions between crops and shallow groundwater is therefore recommended and will help to stabilize yields and balance opportunities and risks caused by the 'labile hydrology' of the Pampas (Nosetto et al., 2009).

With this paper we intend to contribute to a better understanding of the complex interactions between soil hydrology and crop growth within the critical zone. We analysed the impact of different groundwater tables and different land use types on groundwater recharge and agricultural production. An analysis of the water distribution over crops, vadose zone and groundwater is necessary to consider processes like soil moisture redistribution, root water uptake and capillary rise of groundwater. We developed a toolbox consisting of a state-of-the-art dynamic simulation model for agricultural crop growth and a Richards equation-based model for soil water flow.

We used local observations of crop and soil parameters with special attention to a detailed determination of soil hydraulic properties. Furthermore we analysed the sensitivity of soil hydraulic parameters with respect to vertical water flow and yields. This is essential to support model and calibration improvement (De Jong van Lier et al., 2015). After calibration and evaluation we analysed the impact of changes of land use and rising groundwater level on regional agricultural production using long term climate data.

This study resulted from a case study that was carried out within an EU-project and reported by De Wit et al. (2017) and Kroes et al. (2017b).

## 2. Method and materials

### 2.1. Study area

The Pampas of Argentina cover a wide plain of about 54 million ha of fertile lands (Viglizzo et al., 2003). Based on soil and rainfall patterns, the region can be divided into different agro-ecological areas (Viglizzo et al., 2003): i) Rolling Pampas in the centre of the area, ii) Sub-humid Eastern Pampas, iii) Semiarid Western Pampas, iv) Southern Pampas, v) North-Eastern Flooding Pampas, and vi) Mesopotamian Eastern Pampas. Dominating crops are soybean and rotations of the crops maize, wheat and soybean.

We analysed the relation between groundwater and land use in a study area of about 40 million ha or 75% of the Pampas of Argentina (Fig. 1), using a combination of a hydrological and a crop simulation model (see following sections). The grid lines indicate the boundaries of the grid cells applied in the simulation at regional scale. Within the study area we selected 6 sites for the calibration of soybean parameters; the location of these sites was based on data availability and spread over the area.

### 2.2. Modelling tools

We merged different modules for crop, soil water and atmosphere and integrated the two dynamic models SWAP (acronym for Soil Water Atmosphere Plant) and WOFOST (WOrld FOod STudies). SWAP is a dynamic soil hydrological model to obtain soil water pressure head values using the Richards equation (Van Dam et al., 2008; Kroes et al., 2017a) that has been applied in many studies (http://swap.wur.nl/References.htm). WOFOST is a generic crop growth simulation model, of which the principles are explained by Van Keulen and Wolf (1986) and Boogaard et al. (2014). WOFOST has been applied in many studies (e.g. Supit et al., 2012; De Wit et al., 2012; Asseng et al., 2013) at different spatial scales in many regions across the world. In order to simulate the soil carbon and soil nitrogen influence, we added also the module Soil-N (Groenendijk et al., 2016).

The integrated model (Fig. 2) is distributed on internet as version 4 of the open-source model SWAP (http://swap.wur.nl).

The integrated model describes a one-dimensional system that ranges from the top of the soil or vegetation, to the bottom of the unsaturated or saturated part of the relevant soil system. In this study we simulated a soil column of 5.5 m.

SWAP numerically solves the one-dimensional Richards equation for the unsaturated-saturated zone:

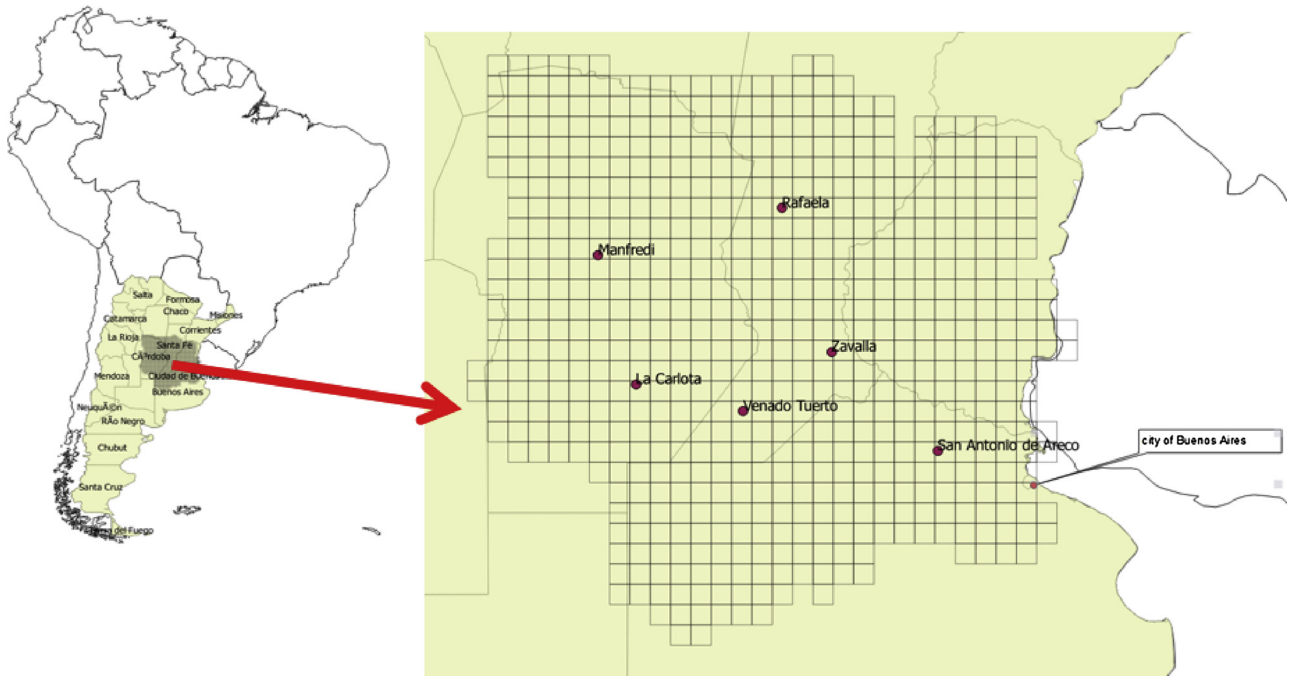


**Fig. 1.** The study area and location of 6 selected sites in the Argentina Pampas. The grid lines delimit the grid cells applied in the simulation at regional scale.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_a(h) \tag{1}$$

where $\theta$ is volumetric water content ($cm^3\,cm^{-3}$), $t$ is time (d), $z$ is the vertical coordinate (cm) taken positively upward, $K$ is the hydraulic conductivity (cm $d^{-1}$), $S_a$ is soil water extraction rate by plant roots ($cm^3\,cm^{-3}\,d^{-1}$) and $h$ is the soil water pressure head (cm).

To solve this equation, specified boundary conditions and soil hydraulic relations between $\theta$, $h$ and $K$ are required. The upper boundary is defined by meteorological conditions which are input to the model and by a cultivation which can be a static or a dynamic type of crop (Kroes et al., 2017a). In this study we used the static sub-model for grassland and the dynamic sub-model WOFOST for both the growth of soybeans and for a crop rotation of soy-wheat-maize.

We used the Penman-Monteith method (Allen et al., 1998) to determine the potential evapotranspiration which is partitioned over potential transpiration of a crop and potential soil evaporation using the Leaf Area Index. Extensive descriptions are given in chapter 3 and appendix 1 of Kroes et al. (2017a).

Rainfall is input to the model as daily amounts. Runoff is calculated when the rainfall intensities supersede the soil infiltration capacity or when the soil profile becomes saturated.

The lower boundary defines the interaction with a regional groundwater flow system. The model has 5 different boundary

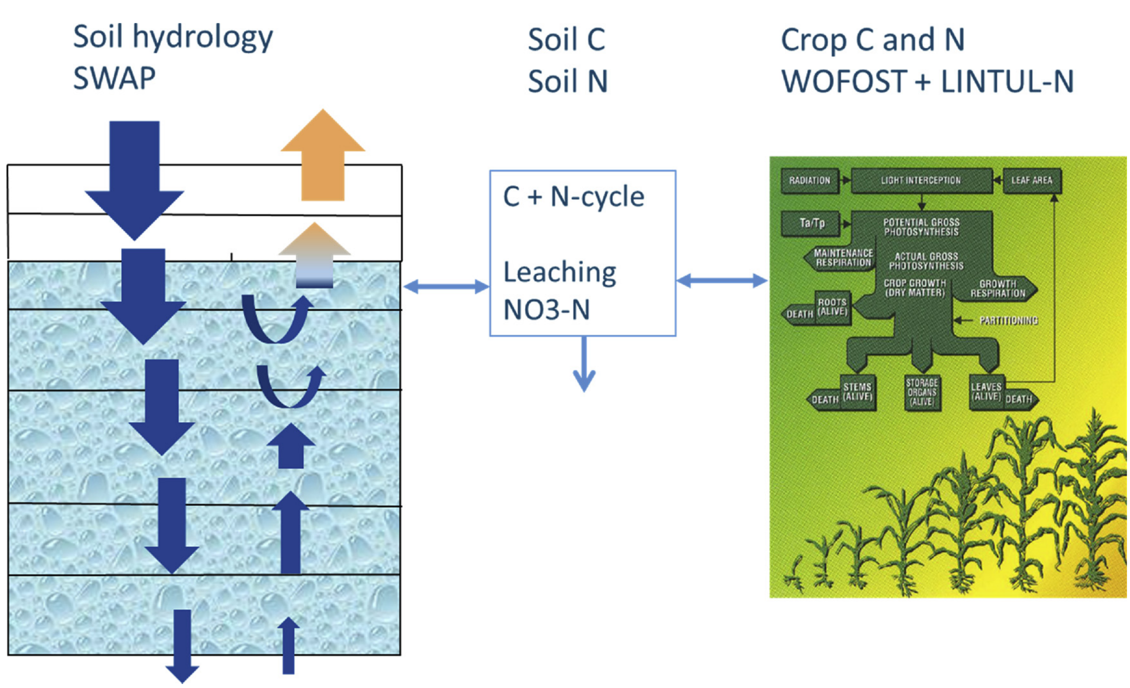


**Fig. 2.** Set of dynamic modelling tools integrated in SWAP version 4.

**Table 1**
Parameters for the Argentinian soils (after Damiano, 2018) used to create the input tables. See Damiano (2018) for units and explanation.

| Code | Location | $b$ | PSIe ($\psi_e$) | PSIi ($\psi_i$) | *Theta* ($\theta_i$) | $D$ | $K_s$ | $f$ |
|---|---|---|---|---|---|---|---|---|
| Ar | Arrecifes | 6.94 | 10.8 | 17.5 | 0.451 | 0.026 | 0.045 | 0.849 |
| AD | Arroyo Dulce | 6.98 | 11.0 | 17.9 | 0.449 | 0.027 | 0.046 | 0.872 |
| Go | Gouin | 7.52 | 13.3 | 21.5 | 0.472 | 0.024 | 0.045 | 0.959 |
| Pe | Pergamino | 7.52 | 14.6 | 23.7 | 0.456 | 0.024 | 0.058 | 0.874 |
| Ra | Ramallo | 7.75 | 16.8 | 27.2 | 0.462 | 0.023 | 0.026 | 0.860 |
| Ro | Rojas | 7.38 | 15.7 | 25.5 | 0.435 | 0.025 | 0.081 | 0.759 |
| SL | Santa Lucia | 7.61 | 14.4 | 23.4 | 0.467 | 0.024 | 0.037 | 0.938 |
| VT | Venado Tuerto | 7.42 | 13.1 | 21.3 | 0.446 | 0.024 | 0.063 | 0.914 |

conditions which are explained in detail by Kroes et al. (2017a). In this study we applied two types of bottom boundary conditions: a) free-drainage and b) Cauchy bottom boundary condition. For the Cauchy condition, the flux through the bottom boundary ($q_{bot}$) is defined by the difference of the hydraulic head ($h+z$) at the column bottom and the hydraulic head $\phi$ (cm) of the regional groundwater below the flow domain described by the model, divided by a hydraulic resistance $c$ (d).

$$q_{bot} = \frac{[h + z]_{z=bot} - \phi}{c} \tag{2}$$

We used a constant hydraulic resistance of 500 days and varied the head of the regional groundwater ($\phi$) to achieve the desired average depth of the fluctuating groundwater level.

As an alternative for the commonly used soil hydraulic functions of Mualem – Van Genuchten (Mualem, 1976; Van Genuchten, 1980), the possibility to supply $\Theta(h)$ and $K(h)$ relationships as tabulated input is implemented. In that way any shape of the relationships can be considered. In this study, the tabular option is used.

The reduction of root water uptake due to too dry or too wet conditions is described according to Feddes et al. (1978). Sometimes only some parts of the root zone are stressed and show reduction of root water uptake, while other parts have favourable conditions for root water uptake. In these conditions the reduction in the stressed parts might be compensated by extra root water uptake in the parts with favourable conditions. Therefore, we extended the Feddes concept with the compensation concept of Jarvis (2011).

To simulate soybean growth, the sequential phenological development pattern in WOFOST had to be adapted. This sequential pattern is typical for cereals and is appropriate for tuber crops (potato, sugar beet), which are crops with a relative simple development pattern. For soybean a hybrid phenological development model was developed taking elements from established models for soybean phenology (Setiyono et al., 2007) but still applying the sequential development stage logic that is needed for WOFOST. Adjustments have been described in detail by De Wit et al. (2017) and were implemented in SWAP 4.

We also implemented a soil nitrogen module and used the RothC-26.3 model (Coleman et al., 1997) for an organic matter module. Both nitrogen supplied to the soil by fertilizer applications and nitrogen obtained from mineralization of organic bounded nitrogen are stored in the soil. Mineralization rates of $NH_4$ and $NO_3$ control the nitrogen mineralization and immobilization in relation to the processes in the organic matter cycle.

Ammonium and nitrate balances were calculated on a daily basis. The leaching of nitrate and ammonium was simulated to be controlled by the stock of mineral N present and the water fluxes leaching through the root zone.

The nitrogen distribution within a crop is predicted in SWAP 4 based on the method described by Shibu et al. (2010). The N-contents of crop residues are calculated in the dynamic crop module and then passed to the Soil-N module.

For soybean we assumed that a large portion of the $N_2$ requirement is supplied by $N_2$ fixation from the air. Furthermore we assume that other factors, especially phosphorus supply, are not limiting. This approach is plausible and seems in agreement with Giller (2001) who states that "*The main environmental factors that constrain $N_2$-fixation in the tropics include limitations of water, nutrients (particularly phosphorus) and toxicities*".

We assumed that 80% of the required nitrogen comes from N-fixation, a value close to the default input value of 75% mentioned by Boons-Prins et al. (1993). The remaining demand was assumed to originate from mineralisation of the organic soil matter. For soybean it implies that nutrient stress can be neglected. The adaptions for soybean and soil nitrogen in SWAP 4 have been described in detail by Groenendijk et al. (2016).

Using this integrated model we intended to account for different feedbacks between atmosphere, plants, soil characteristics, soil water and nitrogen limited crop growth. This allowed us to analyse in detail the impact of different land uses on groundwater recharge.

## 2.3. Field scale

### 2.3.1. Soil physical properties

A large number of soil layers in Argentina was analysed by (Damiano, 2018). He developed a pedotransfer function to obtain the soil moisture retention and hydraulic conductivity function based on soil texture data from the Argentina Pampas. The results of this analysis are the parameters of the Uni-parametric Hutson & Cass (Uni-HC) equations which was processed by Damiano (2018) to determine the soil data for 8 locations in Argentina (Table 1). The equations of the applied soil moisture retention and hydraulic conductivity functions are given by Damiano (2018).

We created input tables for the Swap model with these data and it appeared that some parameter combinations caused a discontinuity in the soil moisture retention curve near the inflection point which we adjusted by smoothing. This required an additional parameter $f$ (Table 1) which we used to multiply the pressure head in the wet part of the soil moisture retention curve.

Parameters for the Argentinian soils (after Damiano, 2018) used to create the input tables. See Damiano (2018) for units and explanation.

To verify the procedure we used a data set, obtained from Damiano (Damiano, 2018) with measured values of the retention curves (n = 78) of the Pergamino soils (typical Argiudoll, silty loam; Soil Survey Staff, 2010). Through these data we calculated the optimal parameters of the equations presented by Damiano (2018). Results are presented in Fig. 3.

The left-hand part of Fig. 3 shows the fitted line and the measured soil moisture retention points. In the right-hand part of Fig. 3 the measured and computed values are plotted against each other, showing a rather good agreement.

### 2.3.2. Parameter calibration for soybean

Data for soybean field tests originated from different sites and were supplied by RECSO (Red Nacional de Evaluación de Cultivares de Soja) and UNR (National University of Rosario experiments) (De Wit et al., 2017). The observations consisted of field data from 1259 experiments over the period 2011–2013 (sowing year) for five different sites:

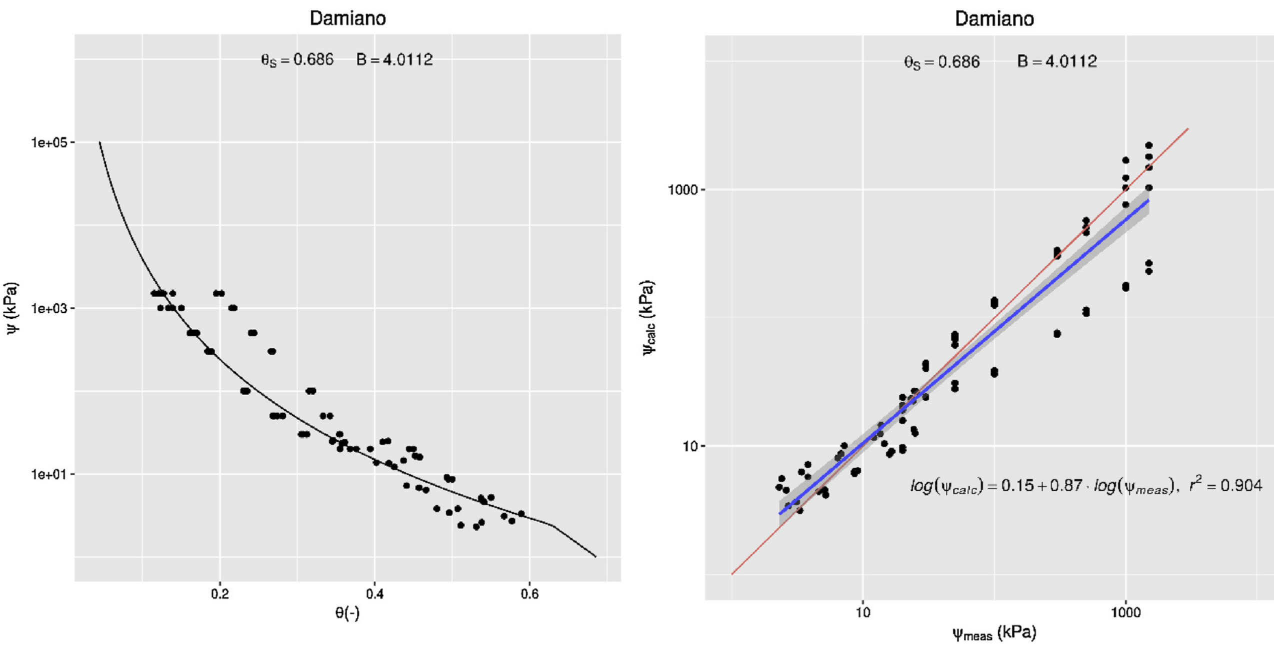


**Fig. 3.** The curve fitted through the points of the measured water retention data of the Pergamino soil (left) and the correlation between the measured and computed pressure heads for a number of moisture contents (right).

**Table 2**
Properties of selected sites to test model results at field scale. Site 2–6 were used for calibration with local field observations and for a 25 year comparison with actual yields from official statistics at county level.

| Site Nr | Site Name | Meteo station | Longitude | Latitude | CaseNr | Sowing date |
|---|---|---|---|---|---|---|
| 1 | San Antonio de Areco | San Antonio de Areco | −59.58 | −34.23 | 2317 | 1-nov |
| 2 | Zavalla | Zavalla UNR WS | −60.88 | −33.02 | 1626 | 14-nov |
| 3 | VenadoTuerto | Venado Tuerto Aero | −61.95 | −33.75 | 2030 | 14-nov |
| 4 | Rafaela | Rafaela INTA WS | −61.55 | −31.18 | 806 | 24-nov |
| 5 | Manfredi | Manfredi INTA WS | −63.77 | −31.82 | 1000 | 14-nov |
| 6 | La Carlota | Rio Cuarto Aero WS | −64.23 | −33.12 | 1881 | 14-nov |

Zavalla, Venado Tuerto, Rafaela, Manfredi and La Carlotta (Table 2 and Fig. 1).

Calibration procedures resulted in a set of parameter for WOFOST under optimal conditions. Procedure and results are extensively described by De Wit et al. (2017). This set was applied in the integrated SWAP-WOFOST model to allow more detailed analyses of groundwater impact.

Since the purpose of the simulations with the integrated model had a focus on the water balance it was necessary to simulate actual yields. This required an additional calibration where we used a so-called management factor to minimize the yield gap, the difference between simulated and observed actual yields. Such a management factor accounts for pests, diseases and farm management, all of them not explicitly accounted for. Our aim was to achieve a single representative value for the management factor which could then also be applied at a regional scale.

### 2.3.3. *Verification of predicted soybean yields at county level*

To verify the calibration results we simulated a longer time series using the boundary conditions from the regional simulations. Results of the 6 sites were compared with official statistics at county level for 6 cases that are located in the same region as the sites with experiments (Table 2). For the 6 cases we varied sowing dates (Table 2) and we assumed a harvest date of 05-April or at maturity, whichever was earlier. Official soybean yield statistics at county level (Min. AGPA, 2016) were converted to dry matter weight, assuming an average 13% moisture content.

### 2.3.4. *Parameter calibration of maize and wheat*

To be able to analyse a crop rotation scheme that consisted of soybean, maize and wheat we tested maize and wheat for a long time series using official statistics at county level and meteorological data for the site San Antonio de Areco (Table 2 and Fig. 1).

We calibrated the maize and wheat input files. For both crops we started with default data sets for the model WOFOST7.1.7 (WofostControlCentre, 2018). We then applied artificial fertilizer (50% $NH_4$-N and 50% $NO_3$-N) at a level of 200 kg/ha N, using a fertilization scheme based on data obtained from field visits in Argentina (Table 3). We calibrated the crop parameters using official yield statistics at county level (Min. AGPA, 2016).

### 2.3.5. *Sensitivity analyses*

To demonstrate the interaction of input parameter on various output values, impact response surfaces (IRS) are commonly used in crop modelling (Fronzek et al., 2018). We investigated the influence of the soil physical properties of the top soil layer (20 cm) on the flux

**Table 3**
Fertilization scheme for maize and wheat.

| Crop | Date of application | Dosage (kg $ha^{-1}$) |
|---|---|---|
| Maize | 03 October | 50 |
| Maize | 15 November | 150 |
| Wheat | 01 June | 125 |
| Wheat | 01 August | 75 |

 

through the bottom of the root zone, which may have positive (upward) or negative (downward) values. We focused on the crop soybean because it is the predominant crop in the region and in our analysis.

We used the results of the calibrated soybean simulation in Zavalla, including meteorological data for four years (2011–2014). Because it was expected that groundwater depth had a large influence on the results, we performed this exercise for eight different groundwater table regimes varying from −500 to −150 cm. The influence of the soil physics of the top layer was investigated by changing saturated moisture content and saturated conductivity input values with a specified percentage. These percentages varied between -50% and +50% with 2% steps.

### 2.4. Regional scale

An analysis of time and space variations of actual yields and groundwater recharge was carried out using a distributed modelling approach.

We introduced five different groundwater conditions and three different land use types which we analysed for their impact on crop yield and groundwater recharge.

#### 2.4.1. Spatial schematization using soil, climate and land use

Spatial schematization was similar to the work by De Wit et al. (2017).

Overlays of maps from different gridded data sets for soil, climate and Gyga-ED zonation were made (De Wit et al., 2017). We used the detailed ISRIC WISE30 s soil map (Batjes, 2015), gridded datasets with meteorological information and a resolution of 0.25° (Fig. 1). The overlays resulted in 2842 unique calculation units which were used for distributed simulations. We used the same local weather data for the 6 selected sites (Table 2) and for the distributed modelling. To evaluate the accuracy an independent evaluation set was constructed and made available by INTA (Instituto Nacional de Tecnología Agropecuaria) using daily data of 178 stations. For each station the most nearby grid cell was selected for each different data source. Minimum and maximum temperature, radiation and precipitation were included. In the vegetation and drought monitoring domain data are usually available at decadal time steps. Finally, it was decided to use different sources of meteorological data for precipitation and global radiation (De Wit et al., 2017).

The rainfall amounts show large temporal differences (Fig. 4) with dry years like 1989 and 2008 that have a low median rainfall of 700 mm $yr^{-1}$ and wet years like 2003 and 2012 that have a median rainfall of about 1200 mm $yr^{-1}$. The wettest years are 2002 and 2012 with values of more than 1600 mm $yr^{-1}$.

The spatial differences of rainfall are large (Fig. 5) especially in wet years 2002 and 2012. Rainfall increases from northwest to southeast.

For the evaluation of land use changes it was assumed that all grids have a dominant land use of either soybean, a crop rotation of soybean-wheat-maize or permanent grassland.

#### 2.4.2. Soil physical parameters

Hydrologic analyses usually involve the evaluation of soil water infiltration, redistribution, percolation, capillary rise and plant-water relationships. To define the hydrologic soil water effects, knowledge of soil water characteristics for water potential and hydraulic conductivity is required. Although measuring these relationships in the field or laboratory is advised to obtain the best results, these measurements are time-consuming and expensive, especially if they have to be done for a large area. Statistical correlations can be found between these soil properties and other, more easily measurable soil variables such as texture, organic matter (OM), and structure. These pedotransfer functions (ptf) can provide estimates sufficiently accurate for many regional analyses and decisions (Saxton and Rawls, 2006). For European soils the HYPRES (HYdraulic PRoperties of European Soils) database of pedotransfer functions (ptf's) has been developed (Wösten et al., 1999). For ptf's of soils from all over the world, another database has been created (Batjes, 2015). The main advantage of these databases is that they enable a direct link between the soil map and the soil physical characteristics. Recently, a review of the present state of ptf's has been published (Van Looy et al., 2017).

For Argentina Damiano (2018) developed and calibrated ptf's using local data (Section 2.3.1). We applied these ptf's to generate soil physical input parameters which we used in our regional analyses. Soil texture parameters for the ptf's were taken from Batjes (2015).

#### 2.4.3. Increasing groundwater levels

We simulated five different groundwater levels ranging from a depth of more than 5.5 m to 1 m below the soil surface (Table 4). The deepest groundwater level was simulated using free drainage as bottom boundary conditions and the other four groundwater levels were simulated using a Cauchy bottom boundary condition. This condition was preferred instead of using a fixed groundwater level, because it generates more realistic fluctuations of groundwater levels and especially more realistic fluxes across the bottom boundary. This becomes especially relevant when simulating transport of several solutes simultaneously, like we did for salinity and nitrate.

We analysed the five different bottom boundary conditions (BBC) using a vertical hydraulic resistance of 500 days and five different regional hydraulic heads (Table 4) in the groundwater aquifer below the simulated soil column of 5.5 m.

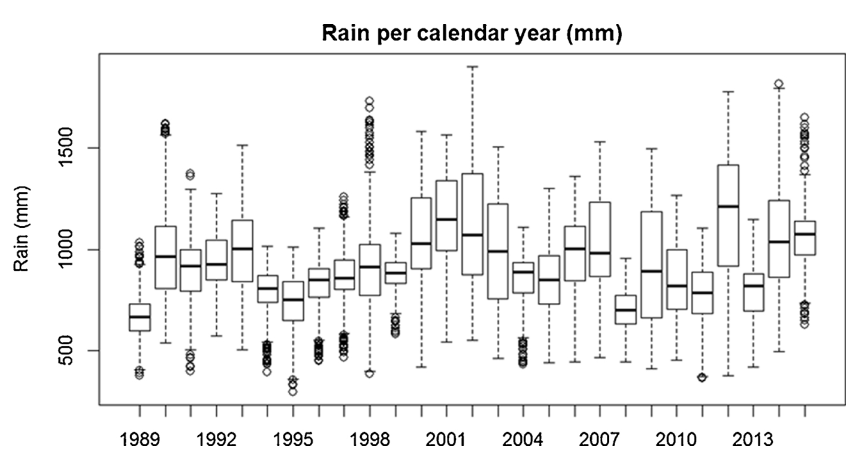


**Fig. 4.** Rainfall (mm $yr^{-1}$) in the Pampas for the years 1989–2015; values are given with a spatial variation as boxplots with median, quartile and extreme rainfall within all grids applied for the distributed modelling.

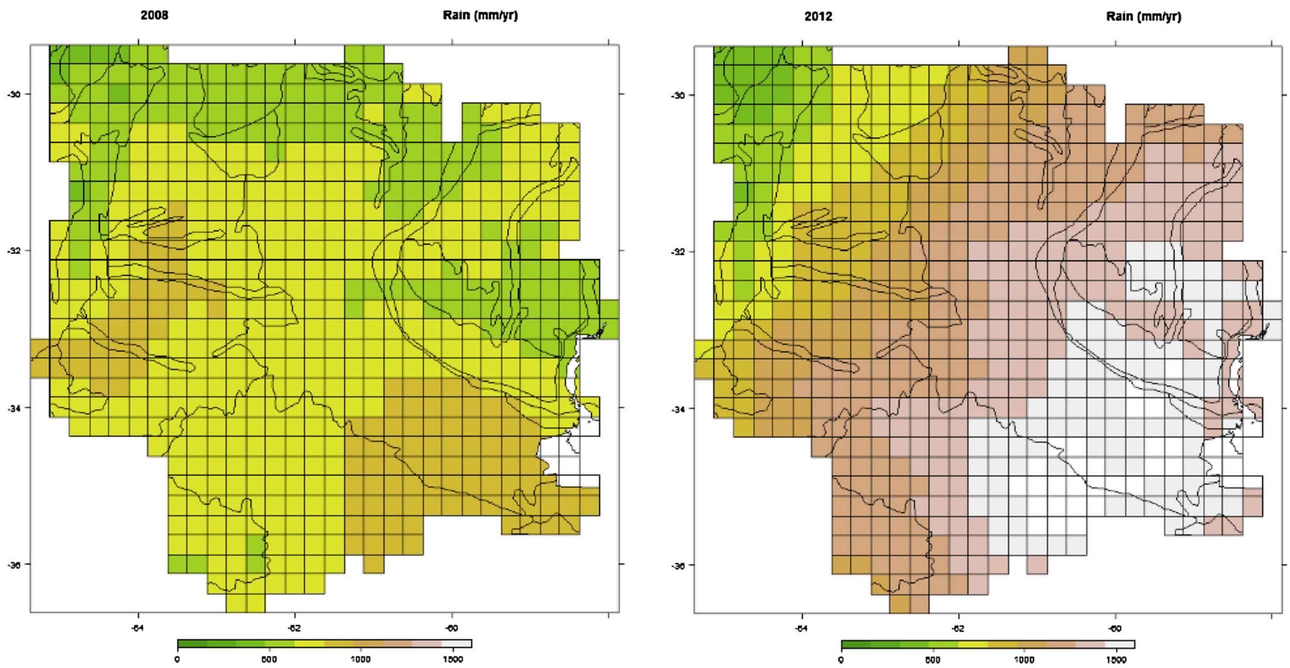


**Fig. 5.** Rainfall (mm $yr^{-1}$) in the dry year 2008 (left) and in the wet year 2012 (right).

**Table 4**
Different bottom boundary conditions (BBC) applied in the regional analyses.

| BBC nr | Regional groundwater head (m below soil surface) |
|---|---|
| 1 | > 5.5 (Free drainage) |
| 2 | 4 |
| 3 | 3 |
| 4 | 2 |
| 5 | 1 |

*2.4.4. Land use evaluation with a crop rotation scheme and permanent grassland*

We analysed the impact of land use changes by changing the land use soybean into i) crop rotations and ii) permanent grassland. These land use changes may well be introduced in practice and occurred in past and present as was described by several authors (Viglizzo et al., 2009; Nosetto et al., 2013; García et al., 2017).

For 3 crops (soybean, wheat and maize) used in a rotation, a preliminary test was executed to obtain realistic yields and phenology (paragraph 2.3.3 and 2.3.4). Subsequently a 25 year period was simulated using a 5-year crop rotation block consisting of the crop rotation sequence listed in Table 5 and fertilizer levels the same as at field scale (Table 3). We introduced a 5-year rotation to allow an introduction of 2 types of early soybean that are characterised by different dates for sowing and harvest (Table 5).

For permanent grassland we used the static modelling option, with a fixed leaf area index and rooting depth development, independent of climatic conditions and no simulation of crop yields. The leaf area index was fixed at a low value of 1.0 and the rooting depth at a value of 30 cm. With these values a low productive permanent grassland with limited transpiration is simulated.

**Table 5**
A 5-year crop rotation sequence applied in the regional analyses.

| Crop | Date Sowing | Date Harvest |
|---|---|---|
| Maize | 01 October year 1 | 15 April year 2 |
| Early Soybean | 01 November year 2 | 25 April year 3 |
| Wheat | 01 July year 3 | 30 November year 3 |
| Late Soybean | 01 December year 3 | 01 August year 4 |
| Maize | 01 October year 4 | 15 April year 5 |
| Early Soybean | 01 October year 5 | 15 April year 6 |

We applied free-drainage as bottom boundary condition for the evaluation of land use (Table 4, BBC nr 1).

## 3. Results

### 3.1. Field scale

*3.1.1. Soybean calibration*

Observed and simulated actual yields for the site in Zavalla (Fig. 6) showed a good fit for the harvest-years 2012–2014. Calibration of the crop parameters resulted in an average potential yield of 5.9 ton $ha^{-1}$. There is a relatively large difference between the simulated potential and simulated actual yields. The difference between potential and attainable yield was reduced by a management factor which was manually calibrated to a value of 0.88 and resulted in an average yield reduction of 0.7 ton $ha^{-1}$. The management factor of 0.88 accounts for crop yield reduction processes, such as weeds, pests and diseases, which cannot be explained/described by our model. This value was regarded acceptable to explain the difference between potential and attainable yield as discussed by Van Ittersum et al. (2013), who mentioned values ranging from 0.75 to 0.85. The remaining difference between potential and actual yield was largely caused by drought during the three years. Finally a mean actual yield of 3.2 ton $ha^{-1}$ was simulated and regarded as a good result given the small difference of about 0.2 ton $ha^{-1}$ between simulated and observed actual yields.

*3.1.2. Actual soybean at six sites compared with official statistics at county level*

We extended the simulations in space and time using 6 locations for a comparison with official statistics at county level.

A result for Zavalla is given in Fig. 7 showing simulated and observed yields for the period 1990–2010, a period for which statistics and model results were available. Simulated yields are higher than observed ones, indicating that we are not able to simulate all stress accurately. Our simulations for the Zavalla field neglect differences caused by variation in soil type, drainage condition and management. The statistics we used for comparison do have this variation in space

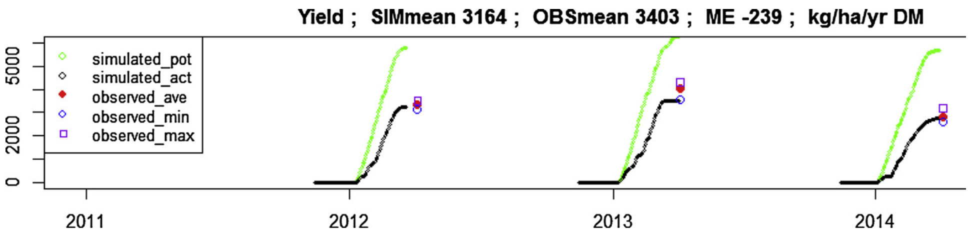


**Fig. 6.** Results for soybean at the Zavalla site: simulated and observed harvested yields of soy beans (kg $ha^{-1}$ dry matter) for the calibration years.2011–2014.

and time. Given these differences in variation we think a long term yield difference of 856 kg $ha^{-1}$ crop $season^{-1}$ is acceptable (Fig. 7).

The average of simulated and observed (official statistics at county level) values show that simulated results show differences similar to the statistics. The largest statistical differences (mean error ME and root mean square error RMSE) occur for Manfredi Rafaela (Table 6).

### 3.1.3. Maize and wheat

A result of the comparison for San Antonio de Areco for grain maize (Fig. 8a and b) and wheat (Fig. 8c and d) showed simulated and observed yields for the period 1990–2010, a period for which statistics and model results were available.

Resulting mean yields are within acceptable ranges. The differences within the statistical observations are larger than the differences within simulation results because the official statistics at county level include all spatial differences, while the simulations results are based on one soil type, drainage condition and management factor. Furthermore the simulated yields of both maize and wheat show much less variation than the observed yields which may also be caused by the use of one cultivar and less variation in soil types and drainage conditions than occurs within the region.

### 3.1.4. Sensitivity analysis

The impact of changes of hydraulic conductivity and moisture content on yield, groundwater recharge, vertical water flow to/from the root zone and runoff was analysed and results are given as IRS-charts of the yearly average values in Fig. 9. Results show that both changing conductivity and moisture content influence the resulting yield and groundwater recharge. Crop yields are especially affected by a low hydraulic conductivity and moisture content (Fig. 9a and b). The analyses of the effect of soil physical parameters on groundwater recharge (Fig. 9c and d) show a larger sensitivity for hydraulic conductivity than

**Table 6**
Observed and simulated soybean yields (kg $ha^{-1}$ DM); Actual and potential simulated yield ($Y_{act}$ en $Y_{pot}$) and observed yield ($Y_{obs}$) and the difference between actual yield and observed yield ($Y_{diff}$) given as average values for the period 1990–2015. Simulated values result from the integrated model SWAP. Observations result from official statistics at county level.

| Location | $Y_{pot}$ | $Y_{act}$ | $Y_{obs}$ | $Y_{diff}$ |
|---|---|---|---|---|
| 1_SanAntonio | 5813 | 3064 | 2408 | 656 |
| 2_Zavalla | 5853 | 3265 | 2408 | 856 |
| 3_VenadoTuerto | 5907 | 2775 | 2537 | 238 |
| 4_Rafaela | 5527 | 3185 | 2264 | 921 |
| 5_Manfredi | 5799 | 3164 | 2003 | 1161 |
| 6_LaCarlota | 5874 | 2659 | 1908 | 751 |
| Average 1-6 | 2255 | 3019 | 764 | 764 |

for saturated moisture content. A more detailed analysis will be given by Wesseling et al. (2018).

## 3.2. Regional scale

### 3.2.1. Historical situation from 1990–2015

For the historical situation a soil hydrological situation with deep groundwater (> 5.5 m below the soil surface) was assumed. This situation was simulated with the model SWAP using a hydrological bottom boundary condition of free-drainage (Table 4, BBC nr 1).

The average results of the spatially distributed simulations for the period 1990–2015 show an actual soybean yield ($Y_{act}$) of 2.8 ton $ha^{-1}$ DM (Dry Matter) and an upward and downward flux across the bottom of the root zone of respectively 99 and 72 mm crop $season^{-1}$ (Table 7). The average downward flux across the bottom of the soil profile (groundwater recharge) is 209 mm $yr^{-1}$.

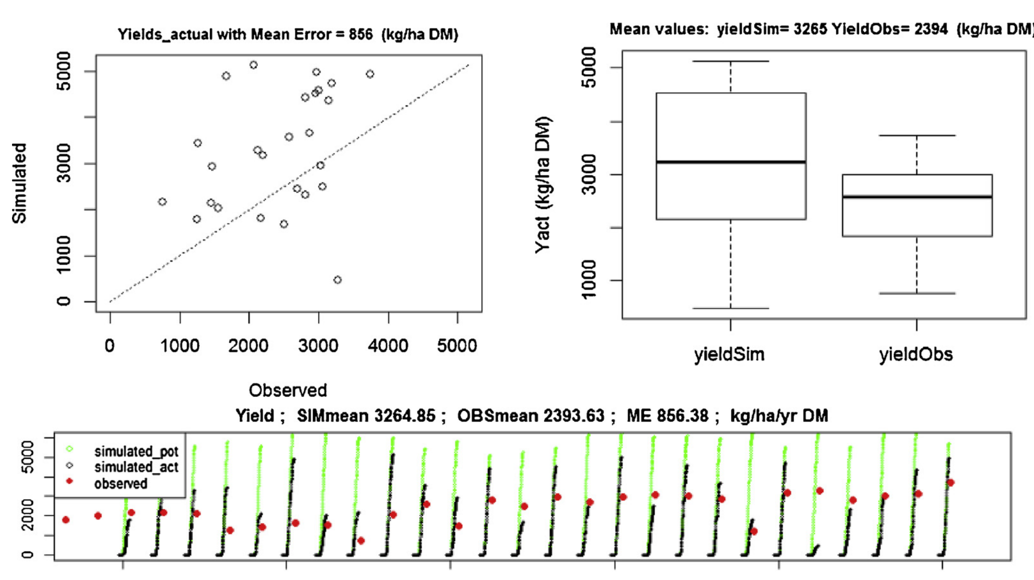


**Fig. 7.** Results for soybean at the site Zavalla: Top left graph shows simulated and observed yields (kg $ha^{-1}$ DM) from official statistics at county level for the period 1990–2015. Top right shows boxplot with median, quartile and extreme values. Lower graph shows the actual yields (kg $ha^{-1}$ DM) during the period 1990–2015.

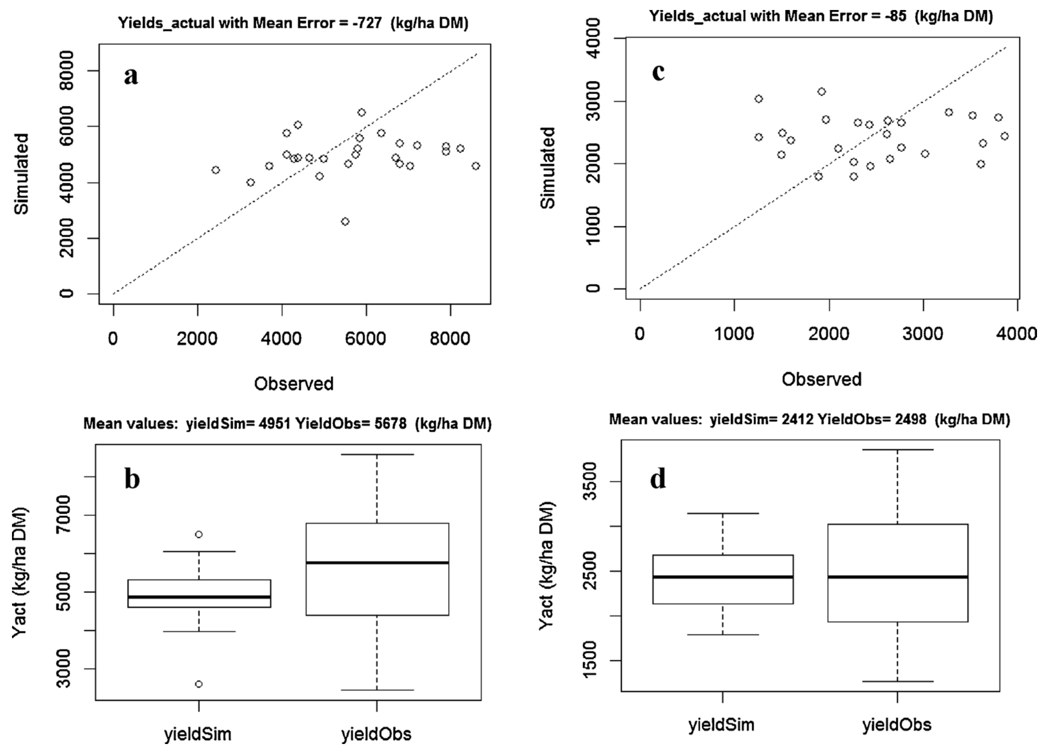


**Fig. 8.** Results for grain maize (a and b) and wheat (c and d) in San Antonio: Upper graphs show simulated and observed yields (kg ha-1 DM) from official statistics at county level for the period 1990–2015. Lower graph shows boxplot with median, quartile and extreme values.

The actual yields and the groundwater recharge in dry 2008 and wet 2012 are presented in Figs. 10 and 11. Soil types can be recognised in the spatial patterns of yield and groundwater recharge.

The groundwater recharge has relatively low median values, but shows a large spatial and temporal variation. In the wet year 2012 groundwater recharge is highest with values of more than 150 mm $yr^{-1}$ in the soils in the NE part of the area.

### 3.2.2. Changes of groundwater levels

Five different drainage conditions were assumed in the simulations (Table 4) which resulted in fluctuating groundwater levels at depths of more than 5 m to 1 m below soil surface. We analysed the impact of drainage conditions on yields and groundwater recharge.

Actual yields of soybean generally benefit when non-saline groundwater gets closer to the root zone.

Actual soybean yields generally benefit when non-saline

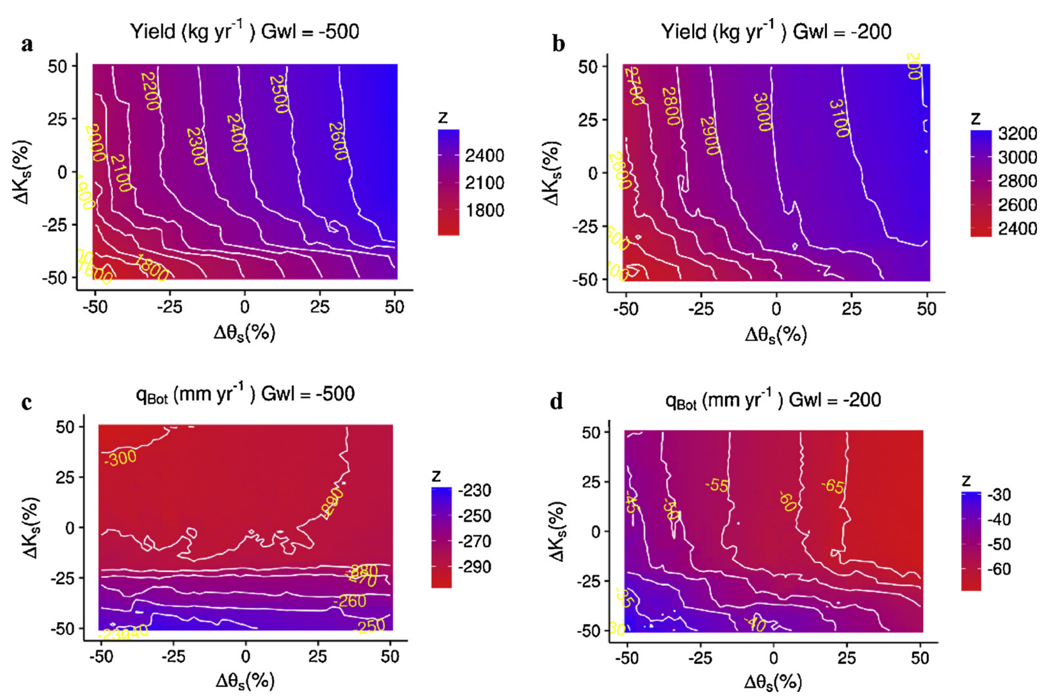


**Fig. 9.** Results of the sensitivity analysis: Impact on yield (kg $ha^{-1}$ $yr^{-1}$) of $K_s$ and $\Theta_s$ using a groundwater level at an average depth of 500 cm (a) and 200 cm (b), and impact on groundwater recharge or bottom boundary flux ($q_{bot}$ in mm $yr^{-1}$) using a groundwater level at an average depth of 500 cm (c) and 200 cm (d).

**Table 7**
Simulation results for soybean: average values for the period 1990–2015. Hydraulic head as bottom boundary condition and average groundwater level (Gwl), actual yield ($Y_{act}$) and potential yield ($Y_{pot}$), actual transpiration ($T_{act}$), vertical flux across the bottom of the root zone during crop growth season, $q_{RZ}^{up}$ is upward, $q_{RZ}^{do}$ is downward flux, $q_{RZ}^{net} = q_{RZ}^{up} - q_{RZ}^{do}$, actual evapotranspiration from soil and crop ($ET_{act}$), and vertical flux across the bottom of the soil profile ($q_{Bot}$, positive values are upward, negative values are downward).

| hydraulic head | Gwl | $Y_{act}$ | $Y_{pot}$ | $T_{act}$ | $q_{RZ}^{up}$ | $q_{RZ}^{do}$ | $q_{RZ}^{net}$ | Rain | Runoff | $ET_{act}$ | $q_{Bot}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| m- soil surface | m-soil surface | kg ha$^{-1}$ DM | kg ha$^{-1}$ DM | mm season$^{-1}$ | mm season$^{-1}$ | mm season$^{-1}$ | mm season$^{-1}$ | mm yr$^{-1}$ | mm yr$^{-1}$ | mm yr$^{-1}$ | mm yr$^{-1}$ |
| > 5.5 | 6 | 2792 | 5753 | 421 | 99 | 72 | 27 | 928 | 18 | 692 | −209 |
| 4 | 4 | 3127 | 5753 | 447 | 125 | 73 | 52 | 928 | 22 | 719 | −180 |
| 3 | 3 | 3567 | 5753 | 479 | 159 | 74 | 85 | 928 | 34 | 755 | −132 |
| 2 | 2 | 4085 | 5753 | 513 | 205 | 73 | 132 | 928 | 74 | 809 | −41 |
| 1 | 1 | 4435 | 5753 | 530 | 248 | 60 | 188 | 928 | 163 | 871 | 110 |

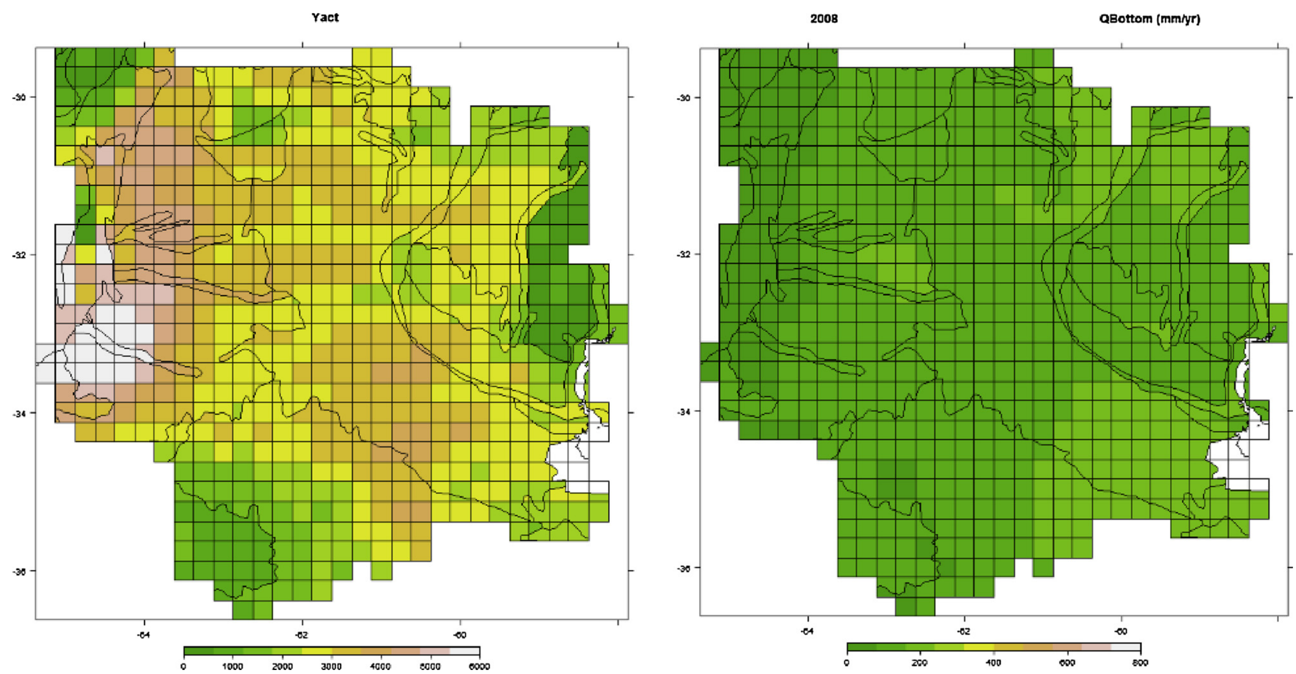


**Fig. 10.** Dry year 2008: Actual Yields (kg ha$^{-1}$ DM) (left) and groundwater recharge (mm yr$^{-1}$).

groundwater gets closer to the root zone. This was similarly predicted by our calculations showing a yield increase from 2.8 to 4.4 ton ha$^{-1}$ with increasing groundwater levels (Table 7). The upward flux to the root zone is 99 mm even in the case of free-drainage and increases to 249 mm when the groundwater level becomes shallow. This upward flux can be partitioned over a recirculation flux and capillary rise (Kroes et al., 2018). In free-drainage scenarios the upward flux is due to recirculation of percolation water and in the other scenarios with groundwater this upward flux is the sum of recirculation and capillary rise.

Simulated crop transpiration increases from 421 to 530 mm during the cultivation period due to upward water fluxes caused by capillary rise and recirculation (Table 7). The average rainfall is 928 mm yr$^{-1}$; runoff increases and is highest in years with shallow groundwater. As groundwater levels increase, the downward flux across the bottom of the soil profile decreases from 209 mm yr$^{-1}$ to an upward flux of 110 mm yr$^{-1}$ under conditions with shallow groundwater.

The simulated flux across the root zone shows positive (upward) values (capillary rise) which increases as groundwater rises and a downward flux which is low and constant (Fig. 12). The increase is caused by the demand of the crop, which is reflected in an increasing yield as function of the upward flux across the bottom of the root zone (Fig. 13). The net flux across the bottom of the root zone increases with a rising groundwater level (Fig. 14), but the net flux across the bottom of the soil profile changes from a downward recharge to an upward extraction which will result in a lowering of the shallow groundwater (Fig. 14).

### 3.2.3. Changes of land use

Three types of land use were simulated with free-drainage conditions: i) no tillage soybean, ii) rotation of maize-soybean-wheat, iii) permanent grassland.

The long term difference in average values of simulated groundwater recharge between crop rotation and soybean is about 1% (Table 8) which is small but has a large spatial and temporal variation with median changes of groundwater recharge that vary between 90% reduction and 55% increase.

Permanent grassland reduces long term average groundwater recharge with 72% from 209 to 59 mm yr$^{-1}$ (Table 8) and has a similar large spatial and temporal variation with median changes of groundwater recharge that vary between 94% reduction and 6% increase

Both the upward and downward vertical flux across the root zone are largest under permanent grassland due to the longer growing season. The downward flux across the bottom of the root zone is highest below grassland, but the bottom flux that contributes to groundwater recharge is lowest under permanent grassland due to its large recirculation flux (Table 8).

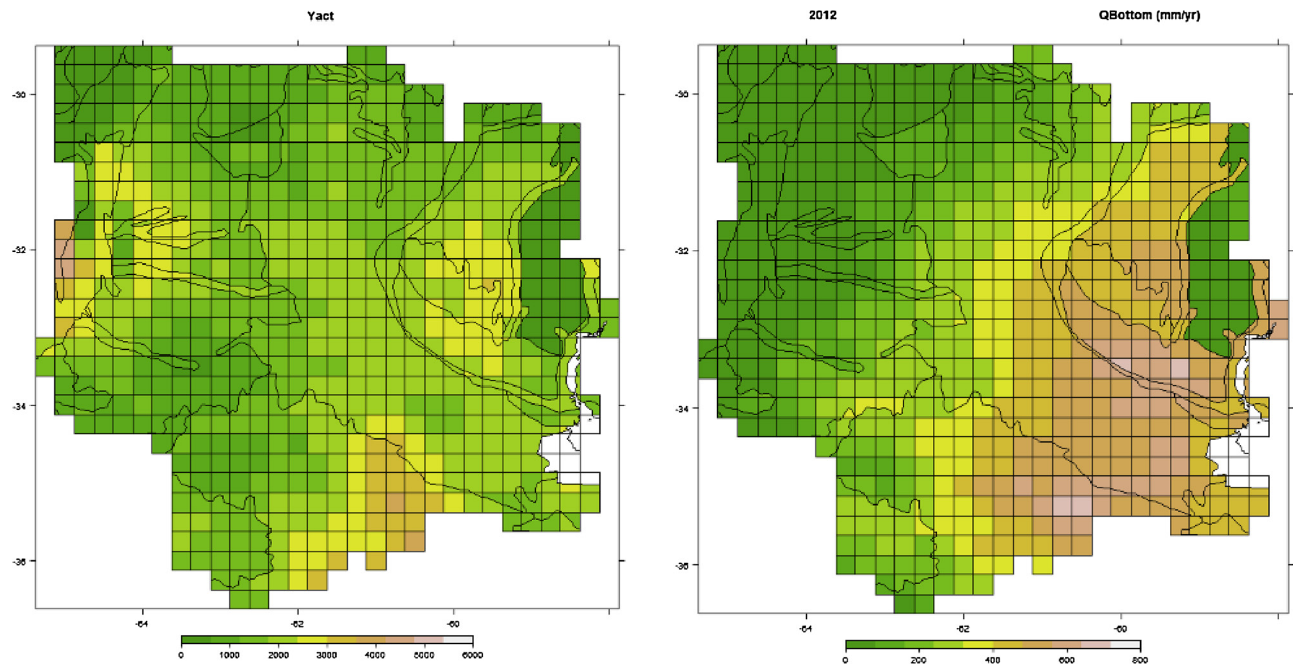


**Fig. 11.** Wet year 2012: Actual Yields (kg ha$^{-1}$ DM) (left) and groundwater recharge (mm yr$^{-1}$).

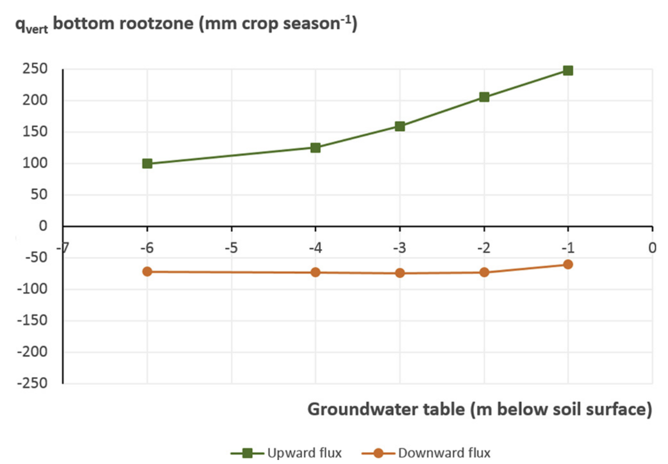


**Fig. 12.** Vertical water flux ($q_{vert}$ in mm crop season$^{-1}$) across the lower boundary of the root zone as function of average groundwater table (m below soil surface); results for 5 different hydrological lower boundary condition; upward flux is positive, downward flux is negative.

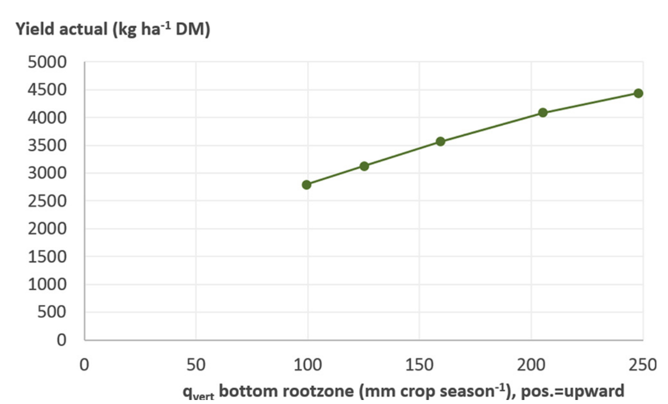


**Fig. 13.** Average actual yields (in kg ha$^{-1}$ DM) as function of upward water flux (mm crop season$^{-1}$) across the lower boundary of the root zone.

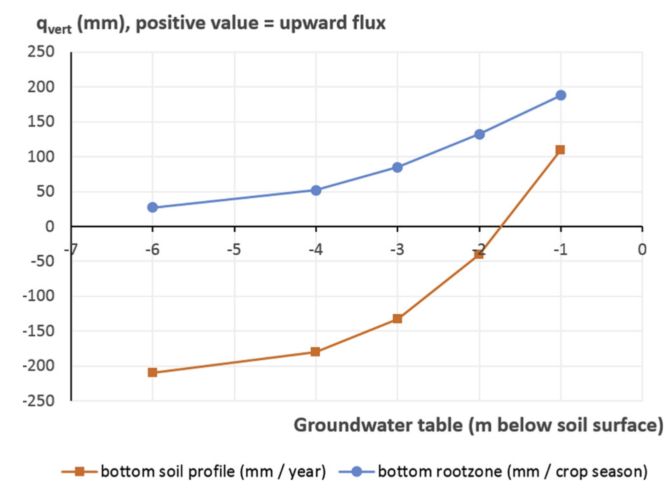


**Fig. 14.** Vertical water flux $q_{vert}$ (mm) across the lower boundary of the root zone (upper figure) and across the lower boundary of the soil profile (lower figure) as function of average groundwater table (m below soil surface); results for 5 different hydrological lower boundary condition; upward flux is positive, downward flux is negative.

### *3.2.4. Changes of land use and nitrate leaching*

A comparison was made for the nitrogen leaching under free-drainage conditions with soybean and the crop rotation. Results show that the nitrate leaching below a crop rotation is about 17% higher than the nitrate leaching below soybean (Fig. 15a). Mean values of nitrate leaching for soybean and crop rotation are respectively 2.3 and 2.7 kg ha$^{-1}$ yr$^{-1}$ N. Mean values for ammonium are 0.2 and 0.3 kg ha$^{-1}$ yr$^{-1}$ N for respectively soybean and crop rotation. Leaching of ammonium hardly occurs because, if ammonium is produced by mineralisation of organic matter, it is rapidly transformed into nitrate by nitrification. The leaching of nitrate shows a large temporal and spatial variation with a larger variation for the crop rotation (Fig. 16b) than for soybean (Fig. 16a).

When one divides the leaching of nitrate-N (2.7 kg ha$^{-1}$ yr$^{-1}$ N) over the groundwater recharge ($q_{Bot}$ in Table 8) this results in an estimated yearly average level of nitrate leaching of about 1 mg l$^{-1}$ $NO_3$-N.

**Table 8**
Simulation results for soybean, a crop rotation and permanent grassland: average values for the period 1990–2015. Free drainage as bottom boundary condition for the 3 cases. Actual yield ($Y_{act}$) and potential yield ($Y_{pot}$), actual transpiration ($T_{act}$), vertical flux across the bottom of the root zone during crop growth season, $q_{RZ}^{up}$ is upward, $q_{RZ}^{do}$ is downward flux, $q_{RZ}^{net} = q_{RZ}^{up} - q_{RZ}^{do}$, actual evapotranspiration from soil and crop ($ET_{act}$), and vertical flux across the bottom of the soil profile ($q_{Bot}$, positive values are upward, negative values are downward).

| Case Description | $Y_{act}$ | $Y_{pot}$ | $T_{act}$ | $q_{RZ}^{up}$ | $q_{RZ}^{do}$ | $q_{RZ}^{net}$ | Rain | Runoff | $ET_{act}$ | $q_{Bot}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg $ha^{-1}$ DM | kg $ha^{-1}$ DM | mm $season^{-1}$ | mm $season^{-1}$ | mm $season^{-1}$ | mm $season^{-1}$ | mm $yr^{-1}$ | mm $yr^{-1}$ | mm $yr^{-1}$ | mm $yr^{-1}$ |
| soybean | 2792 | 5753 | 421 | 99 | 72 | 27 | 928 | 18 | 692 | −209 |
| crop rotation | 2878 | 7439 | 345 | 70 | 66 | 5 | 924 | 17 | 695 | −206 |
| grassland | | | 599 | 168 | 215 | −47 | 924 | 20 | 832 | -59 |

However if one regards the downward leaching of water from the rootzone (66 mm crop $season^{-1}$) the leaching of nitrate has a concentration of 4.1 mg $l^{-1}$ $NO_3$-N which is below the drinking water standard of 10 mg $l^{-1}$ for $NO_3$-N. In some regions higher values are found (Martínez et al., 2014) with large differences in space and time (Aparicio et al., 2008).

## 4. Discussion

Results for actual yields show a large variation for field sites within a region. Aramburu Merlos et al. (2015) estimated actual yields for a larger part of Argentina to be 2.65 ton $ha^{-1}$, based on statistics. We simulated actual yields of 2.79 ton $ha^{-1}$ DM (Table 7). The relatively small difference can be caused by many reasons, such as other groundwater level fluctuations, a different soybean variety or a poor estimate of the management impact.

The calculated soybean evapotranspiration shows a good agreement with results from Nosetto et al. (2012) who determined 670 mm $yr^{-1}$ which is close to the 692 mm $yr^{-1}$ we calculated (Table 8) as long term average for a larger area and a long time series.

In order to lower groundwater levels and reduce the risk of flooding, groundwater recharge should be reduced. A minor reduction will be achieved by changing from monoculture soybean to crop rotations and a larger change will be achieved by changing to other types of land use like permanent grassland or trees. These land use systems will decrease groundwater recharge and contribute to lowering of groundwater levels.

The recommendation for grassland and trees is in agreement with a study by Nosetto et al. (2012) who determined, for a region just north of our study region, high evapotranspiration of 1100 mm $yr^{-1}$ for native forest and eucalyptus plantations compared to 670–800 mm $yr^{-1}$ for herbaceous canopies.

Mercau et al. (2016) explored the impact of different crops on groundwater levels and concluded that crops do not have a substantial effect on the longer term dynamics of the water table. High groundwater levels offer an opportunity which should be carefully considered. It increases capillary rise, allows a more intensive use of irrigation and a higher variety of crops. Frequent on-farm and regional monitoring of groundwater levels should support cultivation strategies.

The simulations showed the sensitivity of yields, evapotranspiration and groundwater recharge for soil physical parameters. Soil physical properties play an important role in the distribution of the precipitation excess. We applied the ISRIC WISE30 s soil map (Batjes, 2015) with world soil property estimates and used it to transform soil texture into model parameters using so-called pedo-transfer (ptf) functions. Several datasets are available for different scales. Montzka et al. (2017)

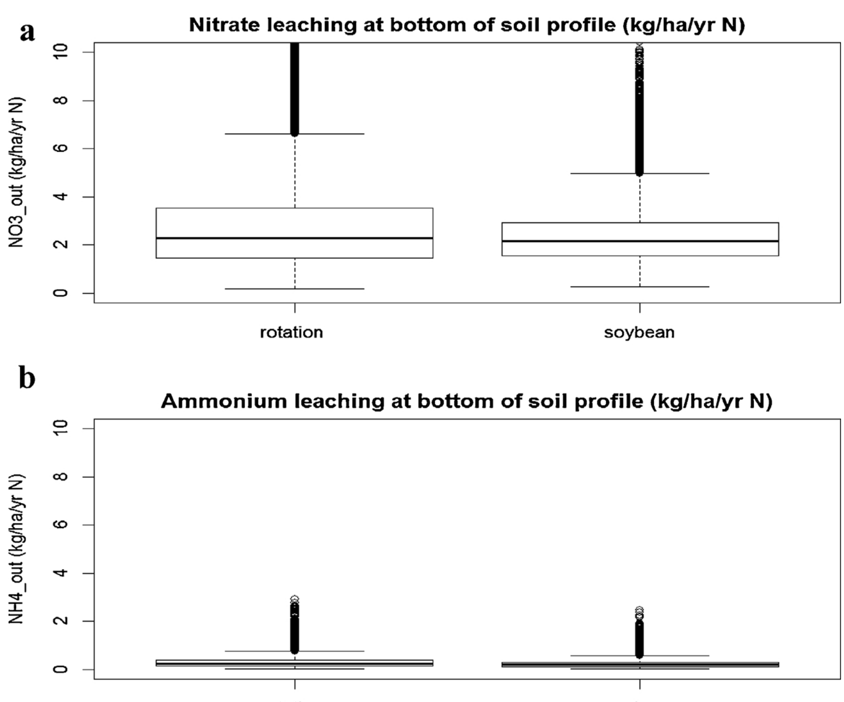


**Fig. 15.** Boxplots with results of downward leaching flux (kg $ha^{-1}$ $yr^{-1}$ N) of $NO_3$-N (a) and $NH_4$-N (b) across bottom of soil profile below crop rotation (left) and soybean (right) under free-drainage conditions.

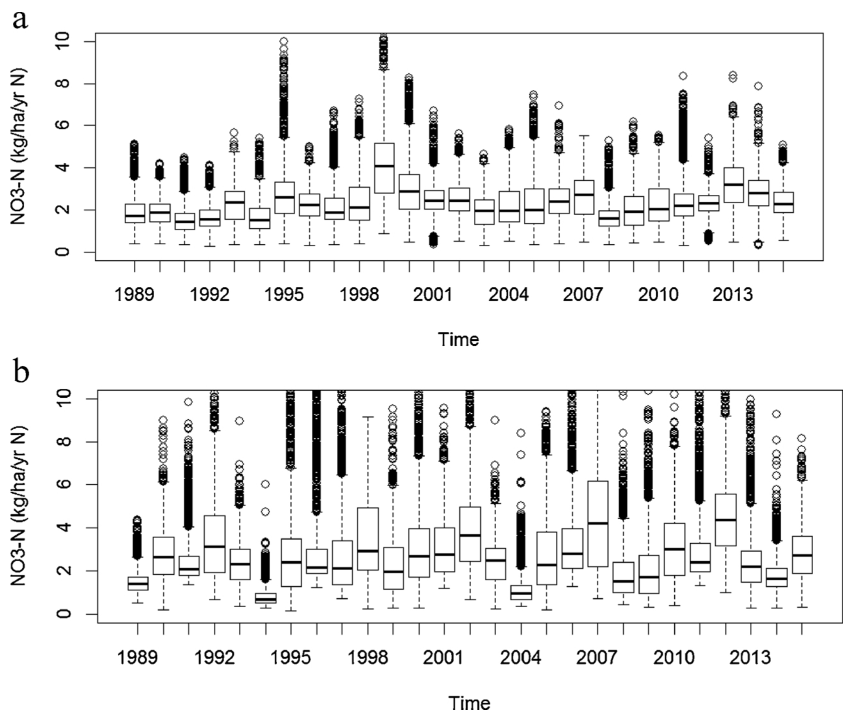


**Fig. 16.** Boxplots with results of downward downward leaching $NO_3$-N flux (kg $ha^{-1}$ $yr^{-1}$ N) across bottom of soil profile below soybean (a) and crop rotation (b).

describe a global dataset based on ROSETTA (Schaap et al., 2001) applied to the SoilGrids1km data set of Hengl et al. (2014). Van Looy et al. (2017) give an overview of ptf's and recommend not to use ptf's beyond the region or soil type from which it was developed. The soils of the Pampas are very a-typical, therefore we refined the parameterisation using local and regional datasets. We used the ISRIC soil map in combination with local soil physical data from Damiano (2018). Further improvements can be achieved using more local soil information.

Long term NT (No Tillage) of soybean cultivation may cause a platy structure of soils in the Argentina Pampas (Sasal et al., 2017a,b) which will have impact on the partitioning of the precipitation excess over surface and subsurface runoff and groundwater recharge. This impact is mainly caused by a rooting depth reduction due to the poor permeability of the platy structured soils. We used a model experiment for the Zavalla site where we varied the maximum rooting depth to quantify the impact of platy soil structure on yield and groundwater recharge. Results show that the actual yields may be reduced from about 2.7 to 1.7 ton $ha^{-1}$ DM and the groundwater recharge may increase from 246 to 331 mm (Fig. 17).

Lowering groundwater without irrigation causes drought and successive crop and yield damage. In the Pampas of Argentina irrigation is marginal. However, rising groundwater may offers more opportunities for irrigation which may increase, contribute to increased evapotranspiration and, as a consequence, lower the groundwater again.

Salinity is an important issue when saline groundwater rises above critical levels (Nosetto et al. (2013). Salinity control measures were evaluated for the Mendoza area by Kupper et al. (2002) who applied the regional hydrological model SIMGRO and concluded that using more groundwater is an effective measure to control salinity in the root zone.

We carried out a regional scale analyses with a salinity level of 3 g $l^{-1}$ in the upward seepage water flux across the bottom boundary for situations with average groundwater levels at 2 and 1 m below the soil surface. Results showed a very low impact on soybean yields. However, this is not representative for the relation between land use and salinization which should be analysed in a broader perspective (Nosetto et al., 2013) because for more salt-sensitive types of land use an increase of salinity may have a large impact.

The use of remote sensing was limited in this study, but future

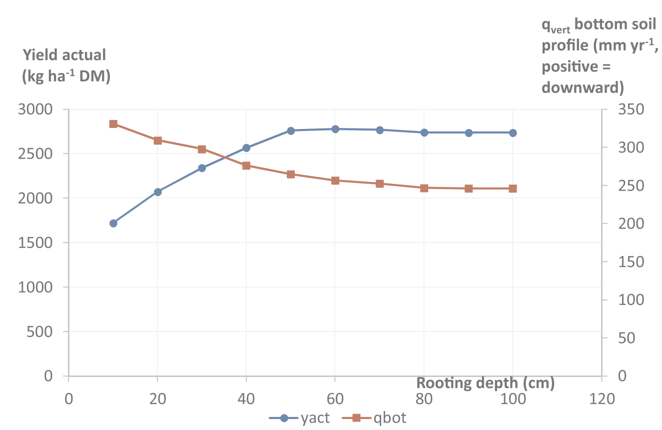


**Fig. 17.** Results of limited rooting depth on actual yield and on groundwater recharge $q_{Bot}$.
Actual yield (kg $ha^{-1}$ DM) and groundwater recharge as flux across bottom of soil profile ($q_{Bot}$ = $q_{vert}$ in mm $yr^{-1}$) as function of maximum rooting depth (cm).

developments will facilitate the increase of its use. Land use maps at field scale level like crop type (needed for rotations) are not easy to obtain for Argentina. New procedures are being developed at INTA to generate new land use maps and facilitate the choice of meteorological data.

This study does not account for all features that influence groundwater recharge. The impact of geological controls in subsoils, impact of steep slopes and processes like ponding are only partially covered and can definitely be improved.

A regional analysis with real-time observations of groundwater levels was beyond the scope of this study. However, several monitoring sites exist (Aragón et al., 2010; Kuppel et al., 2015) and intensification is under way. This may support early warning systems (Viglizzo et al., 2009) and enable a regional study using realistic groundwater levels as bottom boundary or as calibration in future studies.

Opportunities are created when a proper balance is found between

supply and demand of soil water using a larger differentiation of land use. Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels.

## 5. Conclusions and recommendations

Based on several modelling exercises the findings can be summarized as:

- Groundwater recharge from the unsaturated zone and from the root zone shows large differences and should be analysed separately;
- Rising groundwater has an impact on agricultural production with large spatial and temporal differences;
- Rising groundwater may reduce groundwater recharge (negative feedback);
- Crop rotations may increase the risk of nitrogen leaching when compared to monoculture no-tillage soybean;
- Multi-crop rotations may decrease groundwater recharge when compared to monoculture no-tillage soybean;
- Platy soil structure under no-tillage soybean reduces yields and increases groundwater recharge;
- Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels;
- Monitoring of groundwater levels at field and regional scale should be intensified to support early warnings systems and future studies;
- Model analyses support the search to find a proper balance between positive and negative impacts of land use changes.

## Acknowledgements

We thank contributions from the projects SIGMA (Stimulating Innovation for Global Monitoring of Agriculture, grant agreement No. 603719) and WaterVision Agriculture (www.waterwijzer.nl, project KB-14-001-046). Lucas Borrás and José Rotundo provided key knowledge on cropping practices as well as soybean data from yield field trials performed at Facultad de Ciencias Agrarias, Zavalla – Universidad Nacional de Rosario. We thank Marcelo Nosetto for valuable discussions on groundwater dynamics in the Pampas.

## References


Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56. 300 p. Retrieved from. FAO, Rome, Italy accessed on 7 May 2018. http://www.fao.org/docrep/X0490E/X0490E00.htm.

Amundson, R., Richter, D.D., Humphreys, G.S., Jobbágy, E.G., Gaillardet, J., 2007. Coupling between biota and earth materials in the critical zone. Elements 3 (5), 327–332. https://doi.org/10.2113/gselements.3.5.327.

Aparicio, V., Costa, J.L., Zamora, M., 2008. Nitrate leaching assessment in a long-term experiment under supplementary irrigation in humid Argentina. Agric. Water Manag. 95 (12), 1361–1372. https://doi.org/10.1016/j.agwat.2008.06.003.

Aragón, R., Jobbágy, E.G., Viglizzo, E.F., 2010. Surface and groundwater dynamics in the sedimentary plains of the Western Pampas (Argentina). Ecohydrology 4 (3), 433–447.

Aramburu Merlos, F., Monzon, J.P., Mercau, J.L., Taboada, M., Andrade, F.H., Hall, A.J., Jobaggy, E., Cassman, K.G., Grassini, P., 2015. Potential for crop production increase in Argentina through closure of existing yield gaps. Field Crops Res. 184, 145–154. https://doi.org/10.1016/j.fcr.2015.10.001.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 1–6. https://doi.org/10.1038/ncliamte1916. (June).

Batjes, N.H., 2015. World Soil Property Estimates for Broad- Scale Modelling (WISE30sec). ISRIC Report 2015/01. Belmans, C., Wesseling JG, Feddes RA, 1983. Simulation of the water balance of a cropped soil: SWATRE. J. Hydrol., 63, 271-286.

Boogaard, H.L., Van Diepen, C.A., Rötter, R.P., Cabrera, J.M.C., Van Laar, H.H., 2014. WOFOST Control Centre 2.1 and WOFOST 7.1.7 - User's Guide for the WOFOST CONTROL CENTRE 2.1 and the Crop Growth Simulation Model WOFOST 7.1.7. Available at. Accessed last on 21 May 2018. https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-modelsWENR/WOFOST/Documentation-WOFOST.htm.

Boons-Prins, E.R., de Koning, G.H., van Diepen, C.A., Penning de Vries, F.W.T., 1993. Crop-Specific Simulation Parameters for Yield Forecasting Across the European Community. Reports CABO-TT. no 32. .

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R., Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma 81 (1–2), 5–28.

Damiano, F., 2018. Modelización de parámetros hidráulicos del suelo en una cuenca hidrográfica de la región pampeana. J. Soil Sci. AACS, Argentina In press.

De Jong van Lier, Q., Wendroth, O., van Dam, J.C., 2015. Prediction of winter wheat yield with the SWAP model using pedotransfer functions: an evaluation of sensitivity, parameterization and prediction accuracy. Agric. Water Manag. 154, 29–42.

De Wit, A.J.W., Duveiller, G., Defourny, P., 2012. Estimating regional winter wheat yield with WOFOST through the assimilation of green area index retrieved from MODIS observations. Agric. For. Meteorol. 164, 39–52.

De Wit, A., Abelleyra, D., Veron, S., Kroes, J., Supit, I., Boogaard, H., 2017. Technical Description of Crop Model (WOFOST) Calibration and Simulation Activities for Argentina, Pampas Region. EU-SIGMA Report WP4.

Doble, R.C., Crosbie, R.S., 2017. Review: current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater. Hydrogeol. J. 25 (1), 3–23.

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of Field Water Use and Crop Yield. Simulation Monographs. 189 pp. Available at. Pudoc, Wageningen accessed last on 19 May 2018. http://edepot.wur.nl/168026.

Fronzek, S., Pirttioja, N., Carter, T.R., Bindi, M., Hoffmann, H., Palosuo, T., Ruiz-Ramos, M., Tao, F., Trnka, M., Acutis, M., Asseng, S., Baranowski, P., Basso, B., Bodin, P., Buis, S., Cammarano, D., Deligios, P., Destain, M., Dumont, B., Ewert, F., Ferrise, R., François, L., Gaiser, T., Hlavinka, P., Jacquemin, I., Kersebaum, K.C., Kollas, C., Krzyszczak, J., Lorite, I.J., Minet, J., Ines, M., Montesino, M., Moriondo, M., Müller, C., Nendel, C., Öztürk, I., Perego, A., Rodríguez, A., Ruane, A.C., Ruget, F., Sanna, M., Semenov, M.A., Slawinski, C., Stratonovitch, Pierre, Iwan Supit, P., Waha, I., Wang, K., Wu, E., Zhao, L., 2018. Classifying multi-model wheat yield impact response surfaces showing sensitivity to temperature and precipitation change. Agric. Syst. 159, 209–224. https://doi.org/10.1016/j.agsy.2017.08.004.

García, Pablo E., Menénendez, Angel N., Guillermo, Podestá, Bert, Federico, Arora, Poonam, Jobbágy, Esteban, 2017. Land use as possible strategy for managing water table depth in flat basins with shallow groundwater. Int. J. River Basin Manag. 16 (1), 79–92.

Giller, K.E., 2001. 2nd edition. Nitrogen Fixation in Tropical Cropping Systems, vol. 34 CABI Publishing. Field Crops Researchhttps://doi.org/10.1016/0378-4290(93)90012-C. CABI Publishing.

Groenendijk, P., Boogaard, H., Heinen, M., Kroes, J., Supit, I., Wit, A.De., 2016. Simulation of Nitrogen-Limited Crop Growth with SWAP / WOFOST. Report 2721. Alterra Rapport, 2721.

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samul-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., 2014. SoilGrids1km - global soil information based on automated mapping. PLoS One 9.

Jarvis, N.J., 2011. Simple physics-based models of compensatory plant water uptake: concepts and eco-hydrological consequences. Hydrol. Earth Syst. Sci. 15 (11), 3431–3446. https://doi.org/10.5194/hess-15-3431-2011.

Kroes, J.G., Van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R.F.A., Mulder, H.M., Supit, I., Van Walsum, P.E.V., 2017a. SWAP Version 4, Theory Description and User Manual. Wageningen Environmental Research, ESG Report 2780. accessed on 7 May, 2018. http://library.wur.nl/WebQuery/wurpubs/fulltext/416321.

Kroes, J.G., Groenendijk, P., Abelleyra, D., de Verón, S.R., Plotnikov, D., Bartalev, S., Yan, N., Wu, B., Kussul, N., Fritz, S., 2017b. Environmental Impact Assessment of Agricultural Land Use Changes. EU-SIGMA Report WP5.1. Version 2.0. . https://library.wur.nl/WebQuery/wurpubs/fulltext/445875.

Kroes, J., Supit, I., Van Dam, J., Van Walsum, P., Mulder, M., 2018. Impact of capillary rise and recirculation on simulated crop yields. Hydrol. Earth Syst. Sci. Discuss. 22, 2937–2951. https://doi.org/10.5194/hess-22-2937-2018.

Kuppel, S., Houspanossian, J., Nosetto, M.D., Jobbagy, E.G., 2015. What does it take to flood the Pampas? Lessons from a decade of strong hydrological fluctuations. Water Resour. Res. 51 (4), 2937–2950.

Kupper, E., Querner, E.P., Morábito, J.A., Menenti, M., 2002. Using the SIMGRO regional hydrological model to evaluate salinity control measures in an irrigation area. Agric. Water Manag. 56 (1), 1–15.

Martínez, D., Moschione, E., Bocanegra, E., Glok Galli, M., Aravena, R., 2014. Distribution and origin of nitrate in groundwater in an urban and suburban aquifer in Mar del Plata, Argentina. Environ. Earth Sci. 72 (6), 1877–1886. https://doi.org/10.1007/s12665-014-3096-x.

Mercau, J.L., Nosetto, M.D., Bert, F., Giménez, R., Jobbágy, E.G., 2016. Shallow groundwater dynamics in the Pampas: climate, landscape and crop choice effects. Agric. Water Manag. 163, 159–168.

Min. AGPA, 2016. Ministerio de Agricultura Ganaderia Pesca y Alimentacion - Estimaciones Agricolas. accessed on 4-Oct-2016. http://www.siia.gov.ar/sst_pcias/estima/estima.php.

Montzka, C., Herbst, M., Weihermüller, L., Verhoef, A., Vereecken, H., 2017. A global

data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. Earth Syst. Sci. Data Discuss. 1–25.
Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522.
Nosetto, M.D., Jobbágy, E.G., Jackson, R.B., Sznaider, G.A., 2009. Reciprocal influence of crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crops Res. 113 (2), 138–148.
Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B., 2012. The hydrologic consequences of land cover change in central Argentina. Agric. Ecosyst. Environ. 154, 2–11.
Nosetto, M.D., Acosta, A.M., Jayawickreme, D.H., Ballesteros, S.I., Jackson, R.B., Jobbágy, E.G., 2013. Land-use and topography shape soil and groundwater salinity in central Argentina. Agric. Water Manag. 129, 120–129.
Sainato, C., Galindo, G., Pomposiello, C., Malleville, H., de Abelleyra, D., Losinno, B., 2003. Electrical conductivity and depth of groundwater at the Pergamino zone (Buenos Aires Province, Argentina) through vertical electrical soundings and geostatistical analysis. J. South Am. Earth Sci. 16 (2), 177–186.
Sasal, M.C., Léonard, J., Andriulo, A., Boizard, H., 2017a. A contribution to understanding the origin of platy structure in silty soils under no tillage. Soil Tillage Res. 173, 42–48.
Sasal, M.C., Boizard, H., Andriulo, A.E., Wilson, M.G., Léonard, J., 2017b. Platy structure development under no-tillage in the northern humid Pampas of Argentina and its impact on runoff. Soil Tillage Res. 173, 33–41.
Saxton, K., Rawls, W., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1569–1578.
Schaap, M.G., Leij, F.J., Van Genuchten, M.T., 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163–176.
Setiyono, T.D., Weiss, A., Specht, J., Bastidas, A.M., Cassman, K.G., Dobermann, A., 2007. Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. Field Crops Res. 100 (2–3), 257–271.
Shibu, M.E., Leffelaar, P.A., van Keulen, H., Aggarwal, P.K., 2010. LINTUL3, a simulation model for nitrogen-limited situations: application to rice. Eur. J. Agron. 32 (4), 255–271. https://doi.org/10.1016/j.eja.2010.01.003.
Skaggs, R.W., Youssef, M.A., Chescheir, G.M., 2012. Drainmod: model use, calibration and validation. Trans. Asabe 55 (4), 1509–1522.
Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. J. Hydrol. 555, 125–128.
Soil Survey Staff, 2010. Claves para la Taxonomía de suelos. USDA. Dpto de Agricultura USA. Traducción, Ortiz, C & MC Gutiérrez 331p.
Supit, I., van Diepen, C.A., de Wit, A.J.W., Wolf, J., Kabat, P., Baruth, B., Ludwig, F., 2012. Assessing climate change effects on European crop yields using the Crop Growth Monitoring System and a weather generator. Agric. For. Meteorol. 164, 96–111.
Van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of modeling water flow in variably saturated soils with SWAP. Vadose Zone J. 7 (2), 640–653. https://doi.org/10.2136/vzj2007.0060.
Van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.
Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. Field Crops Res. 143, 4–17.
Van Keulen, H., Wolf, J. (Eds.), 1986. Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs. Pudoc Wageningen, the Netherlands 479p. Available at. https://edepot.wur.nl/168025 Accessed on 17 May 2018.
Van Looy, K., Bouma, J., Herbst, M., Koestel, J., Minasny, B., Mishra, U., Montzka, C., Nemes, A., Pachepsky, Y., Padarian, J., Schaap, M., Tóth, B., Verhoef, A., Vanderborght, J., van der Ploeg, M., Weihermüller, L., Zacharias, S., Zhang, Y., Vereecken, H., 2017. Pedotransfer functions in Earth system science: challenges and perspectives. Rev. Geophys. 1–58.
Vazquez-Amabile, G., Bosch, N., Ricca, A.P., Ortiz-de-Zarate, M.L., Rojas, D., Lascombes, J., Parra, V., Duarte, G., Feiguin, M.F., 2013. Evaluation of DRAINMOD Model to Study Groundwater Table Dynamics and N Load in Western Pampas, Argentina. American Society of Agricultural and Biological Engineers Annual International Meeting 2013, ASABE 2013, 3(131595082), 0–13.
Vázquez-Amabile, G.G., Bosch, N., Ricca, A.P., Rojas, D.E., De Zárate, M.L.O., Lascombes, J., Feigun, M.F., Cristos, D., 2017. Napa freática: dinámica, variables de control y contenido de nitratos en suelos de pampa arenosa. Ciencia Del Suelo 35 (1041), 117–134.
Videla Mensegue, H., Degioanni, A., Cisneros, J., 2015. Estimating shallow water table contribution to soybean water use in Argentina. Eur. Sci. J. 11 (14), 23–40.
Viglizzo, E.F., Pordomingo, A.J., Castro, M.G., Lertora, F.A., 2003. Environmental Assessment of Agriculture at a Regional Scale in the Pampas of Argentina, 2003.
Viglizzo, E.F., Jobbagy, E.G., Carreño, L.V., Frank, F.C., Aragón, R., De Oro, L., Salvador, V.S., 2009. The dynamics of cultivation and floods in arable lands of central Argentina. Hydrol. Earth Syst. Sci. Discuss. 5 (4), 2319–2345.
Wesseling, J.G., Kroes, J.G., Campos Oliveira, T., Damiano, F., 2018. Sensitivity and uncertainty analyses of models: much easier than expected!. Paper Submitted to the 2nd International Soil Modelling Conference, 5–7 November 2018.
WofostControlCentre, 2018. WOFOST Control Centre, available at https://www.wur.nl/en/Expertise-Services/Research-Institutes/EnvironmentalResearch/Facilities-Products/Software-and-models/WOFOST/Downloads-WOFOST.htm, last Accessed on 14 May 2018.
Wösten, J.H.M., Lilly, A., Nemes, A., Bas, C.Le, 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185.